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NRL Memorandum Report 3486

Angular Distribution of Laser Light Scattered from Laser-Produced Plasma at High Irradiance

B. H. RIPIN

*Laser Plasma Branch
Plasma Physics Division*

April 1977



NAVAL RESEARCH LABORATORY
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Angular distributions of scattered laser light from Nd-laser-produced plasmas at irradiances of 10^{15} - 10^{16} W/cm ² were measured. Total reflectivities in the range of 20% to 50% are found. The total reflectivity remains approximately constant as the target is rotated from normal incidence up to 50° - 60° implying the existence of a steep density gradient near the critical density and/or absorption of laser light in the underdense region of the plasma. 50-60 deg 10 to the 15-th power and 10 to the 16-th power W/sq cm		

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AB

ANGULAR DISTRIBUTION OF LASER LIGHT SCATTERED FROM LASER-PRODUCED PLASMA AT HIGH IRRADIANCE*

The absorption process of laser light in laser-produced plasmas at high irradiances may be a highly complex phenomenon. Ordinary inverse bremsstrahlung, which is dominant at low incident irradiances and plasma temperatures, is of less importance where laser fluxes are large. Parametric instabilities, large radiation pressure, self-generated magnetic fields, density profile modification, resonant absorption, ion fluctuations, to name a few, may be involved in the absorption process at high irradiance. Much information concerning the absorption mechanism may be contained in a close examination of the non-absorbed portion of the laser light, i.e., the scattered light. Measurements of the angular distribution of light scattered from laser-produced plasmas from planar targets and pellets are reported here. Good laser light absorption ($\sim 50-80\%$) is observed for targets of planar geometry and for pellets whose diameter are much larger than the focal spot diameter. The total reflectivity of the target is observed to be approximately constant for irradiation within $\pm 60^\circ$ of normal incidence and then increases rapidly for irradiation at increasingly small angles to the target surface. This behavior implies that the density gradient near the critical surface ($\omega_L = \omega_p = (ne^2/\epsilon_0 m)^{1/2}$) is very steep (i.e., within a wavelength of the laser light), and/or that significant laser light absorption is occurring in the underdense region of the plasma in the vicinity of one-fourth the critical density.

The experimental arrangement is similar to that described previously.^{1,2} A Nd:Yag-Glass laser beam ($\lambda = 1.064 \mu\text{m}$) is focused

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by either an $f/1.9$ or an $f/14$ aspheric lens onto the surface of a solid target in an evacuated chamber. Both the incident and back-scattered energy is measured on each shot with calorimeters viewing near normal 4° per surface beam splitters in the laser beam path. Backscattered light is defined here as $\sim 1 \mu\text{m}$ radiation scattered back through the focusing lens towards the laser. Scattered laser energy in all other directions was measured either by wrapping calibrated Hadron footprint paper (also known as "burnpaper") completely around the target with only a hole for the incident and backscattered light to enter² or with a calibrated PIN light diode array. One method used to calibrate these diagnostics was by irradiating them with a laser pulse of the same temporal duration and wavelength as the experiment and whose radial energy profile was absolutely measured. In this way thresholds for color changes in the burnpaper film are correlated with the energy flux to within $\pm 20\%$. The array of eight PIN light diodes (MD-2) with broadband IR passing, UV and visible blocking filters (Corning 7-56) were similarly calibrated with the laser source to $\pm 15\%$. Another method used to calibrate the burnpaper was by placing a calorimeter behind a small hole in the film during exposure to $1.06 \mu\text{m}$ scattered laser light. A pyrex shield and filters were used to verify that the burnpaper was being exposed by only infrared and not UV or visible light. Spectra of the scattered light, both backreflection and at several other angles verified that the bulk of the scattered light was within a few nanometers from the incident laser wavelength.

Angular distributions of the scattered light with the target surface normal to the laser beam are shown in Fig. 1 for both $f/1.9$ and $f/14$ focusing lenses. In both cases the incident energy is 10-15 J, 100 psec duration. The focal diameters of the $f/1.9$ and $f/14$ lenses at full laser power are $45 \mu\text{m}$ and $140 \mu\text{m}$ for half-energy content putting the average incident irradiances at 10^{16} W/cm^2 and 10^{15} W/cm^2 respectively. All the PIN diodes except for two at 55° to the target normal are in the plane perpendicular to the incident

polarization. Burnpaper monitored all angles. No strong asymmetry was observed relative to the polarization vector in these experiments although a small fraction of the scattered energy at large angles could have asymmetries not resolved here.³ Each point in these distributions are averaged over about twelve shots with standard deviations as indicated by the error bars. The integral of the scattered energy, assuming azimuthal symmetry, is also plotted versus angle in Fig. 1. Fifty percent of the scattered light falls within a cone angle of about 20 degrees to the target normal with total reflectivity over all 4π steradians of $42 \pm 13\%$ and $30 \pm 10\%$ for the $f/1.9$ and $f/14$ cases respectively. Calibrated burnpaper points are consistent with the calibrated PIN diode results. Other sets of data using the $f/1.9$ focusing lens and burnpaper under somewhat similar conditions yielded reflectivities of 20% ($+15\%$, -5%). The parameters which determine the variation of reflectivity in the observed range of 15% to 55% have not as yet been definitively determined.

The fact that the angular width of both of the scattered light distributions shown in Fig. 1 are approximately equal and wide compared to the solid angles subtended by the lenses themselves, even though the focal spot sizes are different, especially in the $f/14$ case, may indicate that the scattering surface is somewhat rough or that stimulated side scatter is occurring. It is interesting to note that the relative angular distribution for scattered light observed here is almost identical to that published for a somewhat lower intensity and longer pulse duration⁴ and also to experiments with parameters closer to those reported here.³

When the target surface is rotated from normal incidence to the incident laser beam, the bulk of the scattered light falls into one of two classes. First, there is the "direct backscatter" back through the focusing lens, and, second, there is the "specular reflection" which is centered about the target's mirror reflection angle. The specular reflection component has essentially the same angular distribution shown in Fig. 1 except that at increasing angles of

incidence the distribution in the plane perpendicular to the axis of rotation narrows.⁵ This effect may be interpreted to be caused by curvature of the scattering surface.

The sum of the two components which accounts for most of the detectable light, are plotted in Fig. 2 versus the angle between the target normal and the laser beam axis in the case of an $f/1.9$ focusing lens with laser parameters the same as Fig. 1. Both p and s polarization orientations are included. As the target is rotated from normal incidence, the direct backscatter decreases and the specular reflection increases. Up to an angle $\alpha \sim 50^\circ - 60^\circ$ the sum of the two scattering components is approximately constant. At more grazing angles of incidence than $\alpha \sim 60^\circ$ the reflectivity sharply increases. The reflectivity is not sensitive to the incident beam's polarization orientation. Note, also that the angle $\alpha = 60^\circ$, where the reflectivity increases, is much larger than the maximum half-angle (15°) of the $f/1.9$ lens.

The result that reflectivity is approximately constant up through a large angle from normal incidence has important implications. It is well known⁶ that an electromagnetic wave will be reflected at density n_τ (turning point density) below the critical density, n_c , for that frequency if it propagates into a density gradient at an angle θ from the gradient. In plane geometry this turning point density is independent of the density profile and is given by

$$n_\tau = n_c \cos^2 \theta. \quad (1)$$

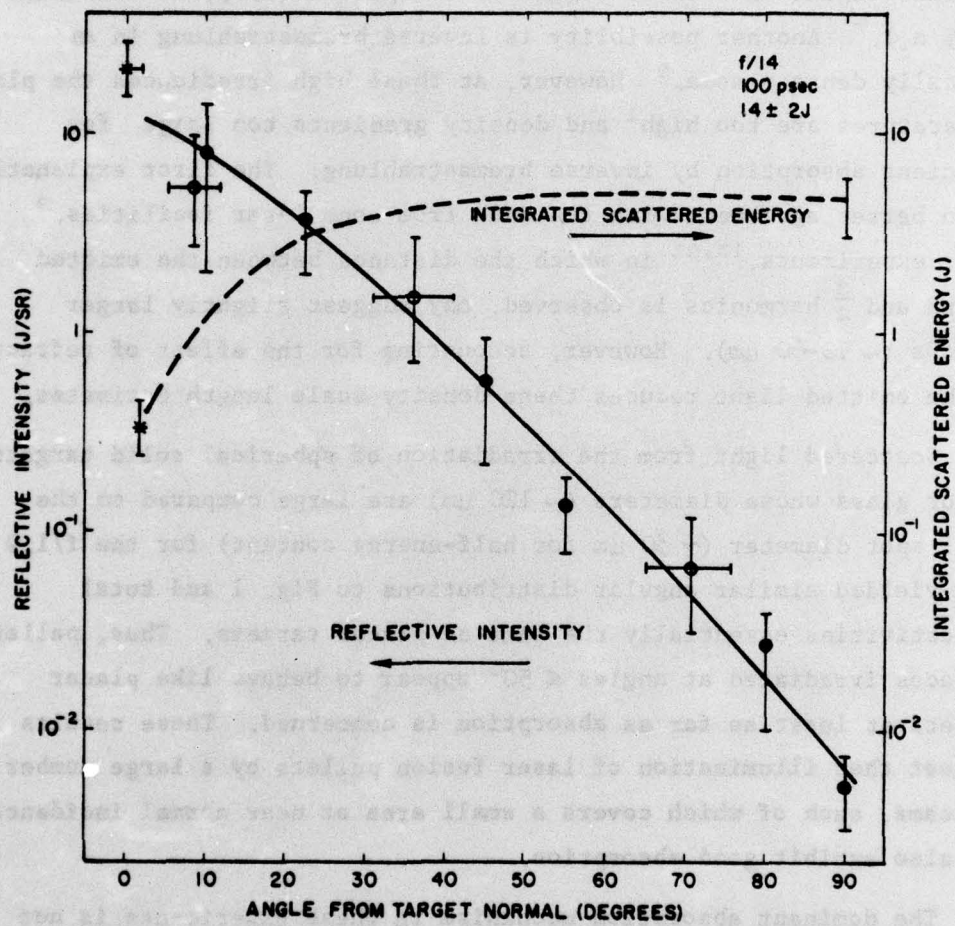
In other geometries the relationship is dependent upon the density profile along the ray trajectory, however, the basic conclusions below are similar. A ray, therefore, with $\theta \sim 60^\circ$, the angle for which the reflectivity in Fig. 2 abruptly increases, has a turning point density $n_\tau \approx 0.25 n_c$. Laser energy can tunnel through and be absorbed at n_c for turning points located within approximately a wavelength

of the critical surface. This implies either one or both of the following conclusions: (1) The density gradient between n_c and $.25 n_c$ is very steep (i.e., within a wavelength of laser light $\sim 1 \mu\text{m}$) if the energy is absorbed at n_c , or (2) The laser energy is absorbed in the underdense region of the plasma (i.e., at densities $\sim .25 n_c$).⁷ Another possibility is inverse bremsstrahlung in an optically dense plasma.⁸ However, at these high irradiances the plasma temperatures are too high¹ and density gradients too large for efficient absorption by inverse bremsstrahlung. The first explanation is in better agreement with the data from some laser facilities.⁹ Other experiments,^{10,11} in which the distance between the emitted second and $\frac{3}{2}$ harmonics is observed, may suggest slightly larger lengths ($\sim 10\text{-}60 \mu\text{m}$). However, accounting for the effect of refraction of the emitted light reduces these density scale length estimates.

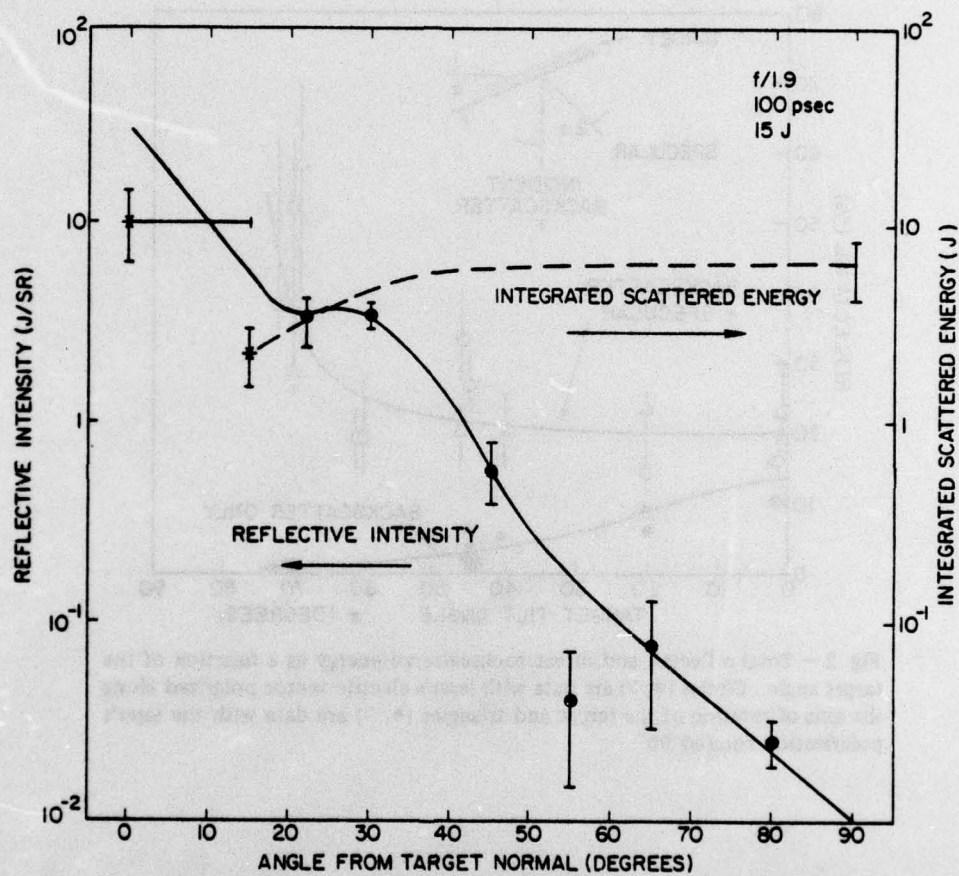
Scattered light from the irradiation of spherical solid targets of CH_2 or glass whose diameters ($\sim 120 \mu\text{m}$) are large compared to the focal spot diameter ($\sim 30 \mu\text{m}$ for half-energy content) for the $f/1.9$ lens yielded similar angular distributions to Fig. 1 and total reflectivities essentially the same as planar targets. Thus, pellet surfaces irradiated at angles $\leq 50^\circ$ appear to behave like planar targets at least as far as absorption is concerned. These results suggest that illumination of laser fusion pellets by a large number of beams, each of which covers a small area at near normal incidence may also exhibit good absorption.

The dominant absorption mechanism in these experiments is not known, however, it must be efficient (50% - 80%) and relatively insensitive to incident irradiation angles.

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(a)



(b)

Fig. 1 — Angular distribution of scattered $1\ \mu\text{m}$ laser light for (a) $f/14$ and (b) $f/1.9$ focusing lenses. Solid lines are the reflective intensity, dashed lines are the integrated scattered energy over all solid angles. Solid circles (●) are PIN diode data, open circles (○) are burnpaper data and (*) is the direct backreflected energy integrated over the lens or averaged over the lens solid angle.

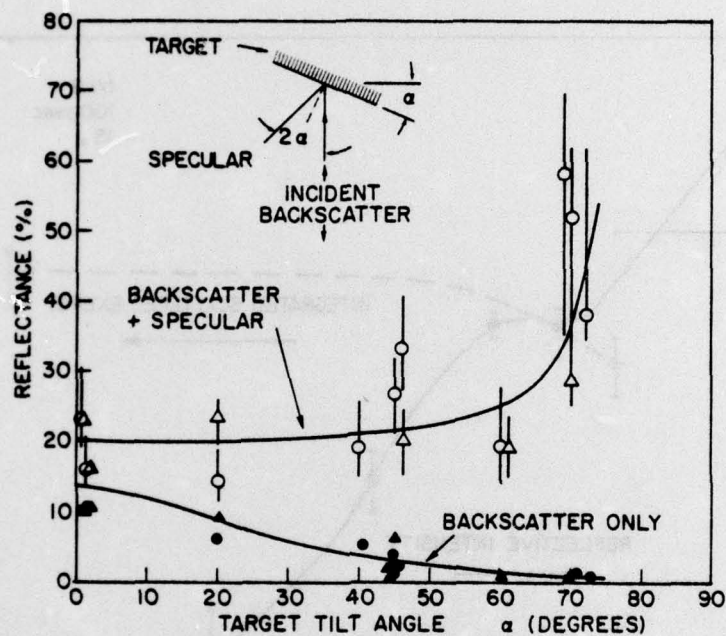


Fig. 2 — Total reflected and direct backscattered energy as a function of the target angle. Circles (●, ○) are data with laser's electric vector polarized along the axis of rotation of the target and triangles (▲, △) are data with the laser's polarization rotated 90°.

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